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The Processing Demands of Higher Order Manual Control: Application of Additive Factors Methodology

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This investigation examines the locus of processing demands of 2nd order manual control, and of tracking a high bandwidth signal, within the framework of multiple resource theory. It is hypothesized that 2nd order tracking may impose greater demands upon perceptual encoding (processing higher error derivatives), central processing (updating a more complex internal model) or response (executing impulse response functions). To assess the locus of demands, in experiment 1, eight subjects performed a

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Sternberg Memory Search task by itself, and concurrently with a first and a second order compensatory tracking task. Following the procedures outlined by Micalizzi & Wickens (1980, Tech. Report EPL-80-2/ONR-80-2), Sternberg variables of perceptual load, central processing load and response load were each systematically manipulated. All three variables were found to produce underadditive effects with the presence or absence of 1st order tracking. That is, their effect was attenuated in the presence of the tracking task. However, the manipulations of perceptual and central processing load were enhanced by 2nd order, as opposed to 1st order tracking, while the manipulation of response load was not. Thus our analyses indicated that the effects of higher order manual control were localized in the perceptual and central processing stages.

Experiment 2 employed an analogous design with a manipulation of bandwidth rather than order. Only four subjects participated. Here the results again indicated underadditivity with the presence of the task. However, none of the three Sternberg variables produced an interaction with tracking bandwidth. Increasing tracking bandwidth required more processing resources but did not differentially affect stages of processing. Thus the locus cannot be clearly specified by the data.

The Processing Demands of Higher Order Manual Control: Applications of Additive Factors Methodology[1]

Based upon the results of a series of experimental investigations, research from our laboratories and others has indicated that human processing resources may be partially dichotomized according to the dimension of stages of information processing (e.g., Navon & Gopher, 1980; Wickens & Kessel, 1979, 1980; Isreal, Chesney, Wickens & Donchin, 1980; Isreal, Wickens, Chesney & Donchin, 1980; Micalizzi & Wickens, 1980; Wickens, 1980). More specifically, this experimental evidence suggests that resources underlying activities of perceptual encoding and central processing (e.g., rehearsal in short-term memory, mental transformations) are functionally separate from those involved in the selection and execution of motor responses.

Assuming that processing resources are in fact partially dichotomized by processing stages, then a task that is exclusively perceptual in nature (e.g., detection of low-intensity signals), should demand resources separate from, and therefore be time-shared efficiently with, a task whose major components involve the selection and coordination of manual responses. In fact, such an empirical relation has been established by Wickens (1976). On the other hand, if a task requires the entire sequence of information processing activities from encoding, through transformation, to response (e.g., tracking, reaction time, transcription), then it is clear that some processing load is placed upon both early and late processing resources. The interesting question in this case concerns the relative demands imposed

upon each. Correspondingly, when such a task is increased in its difficulty, the consequent added demand for processing resources may be imposed upon one or the other or both capacities, and the research question focusses on the locus of increased demand.

Two general approaches may be utilized to establish the locus of demand of a particular task difficulty manipulation: (1) Certain manipulations have obvious a priori justification for being assigned to early versus late processing resources. For example, placing a mask on a reaction time stimulus, or increasing the visual clutter on a tracking display, present obvious examples of "early" processing load. Imposing unpredictable characteristics in the proprioceptive feedback of any control manipulator would clearly influence response load. (2) Alternatively, when task manipulations cannot easily be specified a priori in terms of the locus of processing demand (for example, the number of S-R pairs in a choice reaction time task), then a dual task methodology may be employed. Secondary tasks with well validated loci of demand are performed concurrently with the task in question. To the extent that decrements of these secondary tasks produced from the primary task manipulation are substantial, then the locus of the manipulation is assumed to correspond to that of the secondary task.

Various candidates for secondary tasks have been suggested at one time or the other to "tap" early versus late processing resources. Tasks of a perceptual or cognitive loading nature have included random number generation (Baddeley, 1966), mental arithmetic, or display monitoring, while those of a response nature have included rhythmic tapping (Michon, 1966), or the critical instability tracking task (Wickens & Kessel, 1980; Jex, 1967).

However, two dual task methodologies appear to be particularly sensitive in terms of their locus of effect: The event-related brain potential and the additive factors technique. These will be described in greater detail.

The event-related brain potential (ERP). In a series of experiments, Isreal, Wickens, Chesney and Donchin (1980a,b) have established that the ERP, a transient series of voltage oscillations elicited by a discrete environmental event and recorded from electrodes attached to the surface of the scalp, is sensitive to manipulation of concurrent task difficulty. More specifically, these studies demonstrated that a late positive component of the ERP--the P300--reflected the perceptual/cognitive demands of primary tasks but was uninfluenced by manipulations of response load such as increasing the bandwidth of a concurrent tracking task or generating a series of "open loop" motions with the hand. Thus, as a dual task methodology, the ERP provides one selective probe of "early processing" load.

Additive Factors. Load, the logic of the additive factors method (Sternberg, 1969) is as follows: (1) A reaction time or memory search task is selected as a secondary task. (2) One or more manipulations of this task are then selected and assumed to prolong a particular stage of processing (e.g., a display mask prolongs encoding). The locus of delay incurred by the manipulation is normally well validated through previous research (see Sternberg, 1974 and Pomerantz et al., 1977 for a summary of stage-related effects in the memory search task). (3) When the RT task is imposed as a secondary task, selected manipulations that produce a greater prolongation of RT in the presence of the difficult, but not the easy version of the

primary task (i.e., produce an interaction), are assumed to overlap in resource demands with that primary task manipulation. The additive factors technique has been validated as a dual task methodology in investigations by Briggs et al., 1972; Logan, 1979; Micalizzi & Wickens, 1980. The latter investigation demonstrated a clear interaction between a Sternberg manipulation of display load and the presence or absence of a primary task of monitoring or failure detection. Additivity was observed between this perceptual task and a manipulation of response load.

The experimental issue addressed in the present report concerns the influence of a second tracking difficulty manipulation--the order of the control dynamics--on the stage-defined vector of processing resources. Formally, control order refers to the number of time integrations imposed between deflection of the control device and the response of the plant or system. In first order or velocity control, a constant deflection of the stick generates a constant velocity of the plant, proportional to the stick deflection. In second order or acceleration control, stick deflection produces a constant system acceleration. This behavior is typical of the control of aircraft and many systems with a high degree of inertia. The two relations are expressed as follows:

First order $R(t) = K \int S(t)dt$

Second order $R(t) = K \iint S(t)dt$

Where, $R(t)$ = system response,

$S(t)$ = control stick position.

There appears to be little doubt that systems of higher order impose a greater workload on the operator due to their inherent sluggishness and instability. They generate poorer tracking performance (Chernikoff et al., 1963; McRuer & Jex, 1967; Baty, 1972), are assessed to be of greater subjective difficulty (Wickens & Tsang, 1979), and typically generate greater interference with concurrent tasks (Baty, 1972; Navon & Gopher, 1980; Wickens & Tsang, 1979). It remains unclear, however, precisely where the locus of increased resource demand attributable to second order tracking might fall. In fact, on an a prior basis, a case could be made that increasing system order from first to second might demand more complex processing at each of three processing stages.

Perception. The inherent sluggishness and slow response of second order systems imposes a requirement to anticipate the future system position (or error), so that this, rather than present position, may serve as the basis for initiation of a response correction (Kelley, 1968). An inherent characteristic of systems with a limited bandwidth response is that the best predictions of future position are based upon present velocity and acceleration. Therefore, it may be asserted that an effective strategy in second order tracking is to respond directly to system velocity and acceleration (Fuchs, 1963). In technical control theory terms, this is the requirement of the operator to "generate lead."

While this perceptual adjustment may be desirable for second order control, it appears to extract some cost in operator peformance. There is considerable agreement, for example, that the human visual system either does not "directly" perceive acceleration (e.g., Gottsdanker, 1952;

Gottsdanker & Edwards, 1957; Runeson, 1975), or does not do so efficiently (Rosenbaum, 1975). Fuchs (1962) describes the acceleration cues in second order tracking as being "more subtle," than position or velocity. While there is ample evidence that the visual system does directly perceive velocity, rather than having to compute time-differences in position (e.g., Lappin et al., 1975; Rosenbaum, 1975), it appears, nevertheless, that this perception is more peripherally situated in the visual field. Fuchs' (1962) data suggest that perception of both acceleration and velocity decline relative to the perception of position, with the increased competition for resources imposed by a concurrent task. Moray et al. (1979) have argued that the anticipation required in tracking is a major source of operator workload. McRuer (1980) has noted that the added costs in processing time, imposed by the requirements to process velocity and acceleration, are approximately 200 and 500 msec, respectively.

<u>Central Processing</u>. It is somewhat difficult to distinguish empirically a perceptual from a central processing locus for the demands of higher order tracking, particularly since perceptual and central processes are assumed to draw upon common resources. In each case, positional information is assumed to be differentiated and transformed to rate and acceleration information prior to the selection of the appropriate manual response. The theoretical argument for a central processing locus is that much of manual control is dependent upon the operation of an "internal model" or representation of the system dynamics (Smallwood, 1968; Kleinman, Baron & Levison, 1970; Pew, 1974; Wickens & Kessel, 1980b; McRuer, 1980; Kelley, 1968). This model forms the basis for a mental calculation of the

appropriate manual response to effect a particular change in system state (In essence, computing the inverse transfer function of the controlled system). Accordingly, the higher order system requires mental operations to be performed on a more complex internal model. Formally, a first order system may be completely specified by its input and one state variable, while a second order system requires its input and two state variables.

Response. The role of response strategies in second order tracking assumes a qualitatively different mode of processing. Rather than continuous analog manipulation of the control stick in response to predictive variables (higher derivatives of the error signal), a discrete, time-optimal double impulse response is assumed to be generated in order to minimize an existing error in as short a time as possible. This is accomplished by full deflection of the stick in one direction generating maximum acceleration, followed by full deflection in the reverse for an equal time in order to stablize the system at the new desired location. Such a non-linear strategy is indeed adopted in second and higher order systems when errors are attributable to discrete, step changes in the input (McRuer, 1980), when errors become sufficiently large (Costello, 1968), or when the response of the system is too slow and sluggish to allow direct perception of higher derivatives to occur (VanWyck & Kok, 1978). Less certain is the presence of such strategies when well trained operators are tracking second order systems of shorter time constants (and therefore of greater responsiveness) that are disturbed by band limited random inputs. McRuer and Jex (1967), examining the control power functions of operators tracking under these conditions, reported little evidence for the non-linear

behavior that would be predicted from such a strategy.

Conceivably then, any combination of processing changes at the three stages of processing might be encountered as a consequence of higher order tracking. The relative contribution of adaptation at each stage might furthermore be a function of the level of practice of the subject or the nature of concurrent processing activities (Wickens, 1980b). Specific data concerning the locus of processing changes with increasing tracking order is not easily interpretable in this regard. McRuer and Jex (1967) noted changes in all linear and non-linear parameters of the cross-over model of tracking when control order is increased. Evidence of the locus of interference from secondary tasks is also somewhat ambiguous. Baty (1972) noted a clear deterioration in secondary task performance (a 2 bit tone discrimination task) from first to second order tracking. However, since the discrimination task required all stages of processing, the results are not greatly informative. Navon and Gopher (1980) attribute greater motor demands to higher order tracking but provide no empirical data to directly support this assertion. One source of evidence in favor of early processing adaptation was provided by Wickens, Gill and Donchin (1981), who applied event-related potential methodology to the manipulation of tracking order. Tracking of first and second order systems was performed concurrently with a tone-counting task in which ERPs were recorded to the eliciting auditory stimuli. They observed that the resource-sensitive P300 component of the ERP was attenuated more by second than by first order tracking. Interpreting these data from the point of view of the selective sensitivity of the P300, the authors concluded that the effect of increased order was

localized at the earlier processing stages.

The objective of the current investigation was to apply the additive-factors dual task methodology employed by Micalizzi and Wickens (1980) to identify the locus of processing demands of second order control in a compensatory tracking task. Manipulations of perceptual, central, and response load of an RT task are combined with a manipulation of control order (Experiment 1) and with a manipulation of tracking bandwidth (Experiment 2). Following the logic of Micalizzi and Wickens (1980), the enhancement of the effect of a Sternberg manipulation at the more difficult tracking level is assumed to provide evidence concerning the locus of the difficulty manipulation.

METHOD: Experiment 1

Subjects

Eight right-handed male graduate and undergraduate students from the University of Illinois were recruited to participate in this study. All subjects had normal or corrected vision and were paid $2.50 per hour plus additional bonuses for their participation. Each subject was run individually.

Apparatus

Subjects were seated in a light and sound attenuated booth containing a 10 cm x 8 cm Hewlett-Packard Model 1330a CRT, a dual-axis joystick operated with the left hand, and a spring-return pushbutton keyboard operated with the index and middle fingers of the right hand. Subjects sat approximately 90 cm from the display. A Raytheon 704 sixteen bit digital computer with 24K memory was used to generate the experimental displays and record subject

performance.

Tasks

Sternberg task. The general Sternberg paradigm required subjects to respond as rapidly and accurately as possible to visually presented letters. Specifically, at the beginning of a trial, a fixed number of standard block upper case letters appeared on the display for study. These letters, hereafter referred to as the positive set, were drawn randomly from a subset of the alphabet (Q, Y, and I were excluded due to identification problems in the perceptual load condition discussed below). After ten seconds, the display cleared and a two-minute trial began in which a series of single test letters were presented inside a 1 cm square box in the center of the display. Interstimulus intervals varied randomly between three and seven seconds. If the presented letter matched one of the letters in the previously memorized positive set, the subject responded "yes" by pressing the right key with the middle finger of his right hand. A non-match required a "no" response with the index finger depressing the left key. Target probability was fixed at .5.

In the baseline or reference condition two letters comprised the positive set. Three additional conditions-- perceptual load, central processing load, and response load--modified this condition to produce additive effects on reaction time.

In the perceptual load condition, a grid of line segments was placed over the 1 cm box to retard identification of the letter stimuli. Pretesting of different grid densities and letter stimuli produced a grid pattern that served to prolong single task reaction times relative to the

baseline condition and eliminated the letters Q, Y, and I as possible stimuli.

In the central processing load condition, the memory set size was increased to four letters. The intent of this manipulation was to increase memory search time independednt of the time required for identification and response (Sternberg, 1969).

In the response load condition, subjects were required to press two buttons in succession in order to record a specific response. To respond "yes", the subject had to press the right key with his middle finger first, then the left key with his index finger. "No" required the reverse order. A time window of .3 to .6 seconds was allowed for the second key response. Responses outside this window were recorded as nonresponses by the program.

Tracking task. A single-axis compensatory tracking task required subjects to null an error cursor that was displaced horizontally by a random forcing function with a cutoff frequency of .3 Hz. The error cursor was controlled by left-right movement of the dual-axis joystick with the left hand. Both first and second order system dynamics were utilized.

Under single task conditions, the error cursor and its reference point were located in the center of the display. Under dual task conditions, the tracking task was displayed directly above the 1 cm box.

Design

A within subject design was employed in which each subject participated in all experimental manipulations over a period of six sessions. Each session contained 18 trials: 4 single task Sternberg conditions, each replicated (8); 2 single task tracking trials of either first or second

order dynamics; and 4 Sternberg conditions paired with the tracking task, each replicated (8). Tracking dynamics were fixed for a given session and counterbalanced across subjects, producing three sessions of first order tracking and three sessions of second order tracking.

Trial order within a session was blocked with the ten single task trials always occurring before the dual task trials. Trial order within each of the two blocks was randomized with one exception. The last two single task trials and the first two dual task trials required double key responses. This order was constant due to subject difficulty in switching between single and double key response conditions.

Procedure

Two practice sessions preceded the six experimental sessions. All tasks were practiced until stable performance resulted.

Each experimental session of 18 trials lasted approximately one hour with sessions run on separate days. Perfortmance on the first two single task tracking trials was averaged and used as a baseline measure. Subjects were instructed that subsequent tracking performance in dual task conditions should be equivalent to this baseline. Tracking was thus designated as the primary task and any dual task performance decrements should be reflected in the Sternberg tasks. This instruction was implemented with a monetary bonus system which rewarded dual task performance if and only if tracking performance equalled its baseline level. After each trial, subjects received feedback concerning task performance and bonus amounts earned, if applicable.

Results: Experiment 1

Table 1 presents the summary data for the last six sessions, averaged over replication and sessions. Because there were a number of specific hypotheses to be tested within the array of single and dual task data, these are represented graphically in the format of Figures 1 & 3. Each of the three panels of Figure 1 represents the effect of one Sternberg manipulation: perceptual load, central load, and response load in Figures 1a, b, and c, respectively. Thus the left hand points in all three panels are identical with each other and represent the reaction time collected in the baseline condition (no mask, set size 2, single response). The right hand point in each panel represents the difficult level of the respective Sternberg manipulation: the mask (2A), set size 4 (2B), and the double response (2C). The three lines in each panel represent the effects of the Sternberg manipulation on reaction time during single task, first order, and second order tracking conditions.

In the statistical analysis that follows, separate ANOVAs are performed on the data in each panel because the influence of each Sternberg manipulation, independent of the other two, is of interest. We acknowledge that such multiple testing can increase the probability of a Type I error (falsely rejecting the null hypothesis). The reader may interpret these results with caution accordingly. In all of the ANOVAs to be discussed below, the level of practice variables failed to show a reliable effect and did not interact with the other variables of interest. Thus we feel relatively confident that the pre-training provided to the subjects was sufficient to bring them to a stable level of performance.

<u>Effect of Sternberg variables</u>. It was important to demonstrate that each of our Sternberg manipulations were effective in prolonging single task reaction time. Pilot data had established this fact, and the study of Micalizzi and Wickens (1980) demonstrated longer RTs for the perceptual and response manipulation. In the present data, three three-way repeated measures ANOVAs (phase x replication x Sternberg difficulty) were run on the single task data of Figure 2. The perceptual, central processing, and response load manipulations all exerted reliable effects on single task RT ($F = 8.07$, $p = .04$; $F = 24.89$, $p < .01$; $F = 8.23$, $p = .03$, respectively).

<u>Impact of the tracking task</u>. The effect of diversion of processing resources to the tracking task on Sternberg task performance is revealed by comparing the two lower curves of Figure 1. It is apparent that some competition for resources did exist since reaction time is clearly prolonged in the presence of the first order tracking task relative to the single task control. ANOVAs conducted on the single and first order dual task data revealed the main effect of task load on RT to be highly reliable ($F = 35.7$, $p < .01$; $F = 61.7$, $p < .01$; $F = 72.9$, $p < .01$ for Figures 1a, b, and c, respectively). Correspondingly, the influence of the Sternberg variables was again reliable when the single and dual task data were combined. However, this effect was only marginally significant for the response load manipulation (perceptual: $F = 7.7$, $p < .03$; central: $F = 23.9$, $p < .01$; response: $F = 4.0$, $p = .09$). The joint effect of the tracking task load and the Sternberg variable manipulations produced an additive or slightly underadditive effect in all three cases. The reliability of the interaction term was, perceptual: $F = 1.2$, $p > .10$; central: $F = 6.6$, $p = .05$; response:

$F = 7.8$, $p = .04$. Thus the influence of all three Sternberg variables was either unchanged or slightly attenuated in the presence of the tracking task.

Impact of tracking order manipulation. The increase in tracking order produced a partially reliable increase in the Sternberg RT measure. The main effects on the three manipulations were, perceptual: $F = 8.64$, $p = .02$; central: $F= 4.40$, $p = .07$; response: $F = 2.41$, $p > .10$. Of considerable theoretical interest to the hypothesis under investigation here, the manipulations of perceptual and central processing load both interacted positively with control order ($F = 6.87$, $p = .03$; $F = 8.87$, $p = .02$, respectively). That is, the effects of both Sternberg manipulations were amplified under second order tracking. The interaction effect of response load was not statistically reliable ($F = 1.51$, $p > .10$).

The analysis of Sternberg RT errors indicated that the only reliable effect on this variable was the main effect of Sternberg condition. More errors were made in the double response condition. However, this effect did not interact with tracking load. Therefore we conclude that the pattern of results were not likely to be attributed to a speed-accuracy tradeoff.

Effect on tracking performance. Ideally, in a secondary task investigation of this sort, primary task (tracking) performance should remain unchanged throughout all secondary task manipulations. Wickens (1980c) has argued that this may be an unrealistic expectation. What is critical to establish is that different decrements in secondary task performance are not merely the result of differential tradeoffs between the primary and secondary tasks but are truly related to the differential

competition for resources. Primary task performance (RMS tracking error) is plotted in Figure 2. In the ANOVA conducted on these data, the main effects of Sternberg load (none, easy, perceptual, central, response), tracking order, and the interaction were all statistically reliable ($F = 6.39$, $p < .01$; $F = 31.5$, $p < .001$; $F = 3.49$, $p = .02$, respectively). The effect of tracking order was clearly anticipated. The nature of the effect of the Sternberg manipulation is slightly unexpected. Tracking performance appears to be improved slightly as a function of the addition of the Sternberg task requirement, and to be improved a bit further as the Sternberg task was made more difficult. It is possible that these effects reflected an overly successful effort by the subjects to guard primary task performance. However, the nature of the effect is also consistent with a model of cerebral allocation of resources proposed by Friedman and Polson (1980), to be discussed later. The marginally reliable interaction term and the form of Figure 2 suggest that the Sternberg task effects on tracking error were amplified slightly under second order tracking. However, it should be noted that this effect accounts for only a very small proportion of the total variance.

A factor of considerable importance to the interpretation of interactions in the RT measure is the existence of tradeoffs on the tracking data. The interpretation of a Sternberg interaction might be nullified to the extent that an interaction between variables, of the opposite sign is found in the tracking data. That is, the effect of a Sternberg manipulation on RT might be enhanced in second as opposed to first order tracking, but the effect on RMS error might be <u>attenuated</u> in second order tracking. To

examine this, the dual task tracking error data were analyzed in the same three 2-way ANOVAs as were employed on the Sternberg data. The corresponding data are shown in Figure 3. In Figure 3a the main effect of the perceptual load increase on reducing tracking error is marginally reliable ($F = 4.95$, $p = .06$). Of greatest importance is the significance of the interaction term ($F = 10.34$, $p = .01$). This suggests that the reduction in tracking error was greater with second than with first order tracking. Since this interaction is of the opposite sign from that observed with the RT data (e.g., an attenuation of effect with increased order rather than an enhancement), it is possible that a resource tradeoff may be involved here. With neither the central load nor response load manipulations did a corresponding problem arise, since in neither case was the interaction term reliable ($F = 1.64$, $p > .10$; $F < 1$, $p > .10$, respectively). In the former case, the Sternberg load produced a marginally reliable effect on tracking performance ($F = 3.82$, $p = .09$). In the latter case the effect was not reliable.

Decrement score analysis. As a final means of assessing the resource competition hypothesis, measures of the combined decrements of both measures from their single task levels were computed and analyzed in the identical format to the data represented in Figures 1 & 3. The primary purpose of this analysis is to determine if, when combined together, the decrements (or differences in decrements) in the reaction time data outweigh the increments (or differential increments) in tracking performance. In this way a measure is obtained that reflects the total competition for resources, independent of a tradeoff in allocation (Wickens, Mountford & Schreiner, 1981).

To perform such an analysis, it was necessary to derive a weighting function that allowed for the combination of the two different dependent variables. This was accomplished initially by establishing for each the total contribution to its variance that was not associated with the two theoretical variables of interest (Sternberg and tracking load), with their interaction or with the main effect of sessions. This residual measure of variability was then radicalized and became the normalizing denominator for the raw decrement (single minus dual) scores of each variable. The decrements in each condition for each subject were then summed, and these were treated as the raw data for the ANOVAs.

The decrement data in Figure 4 are plotted in analogous fashion to those in Figures 1 and 3 and seem generally to reinforce the effects observed on Sternberg RT in Figure 1. That is, if we consider the dependent variable to reflect the total cost to performance on both tasks imposed by their concurrence, we note (1) that the second order tracking magnifies this cost (the second order decrements are greater than the first). However, this effect is not statistically reliable ($F = 2.18$, $p > .10$). (2) The effect of second ordedr tracking on concurrent cost is amplified by increases in perceptual load ($F = 8.12$, $p = .02$); central processing load ($F = 12.2$, $p < .01$), and response load ($F = 5.1$, $p = .06$). These results suggest that the pattern of effects observed in Sternberg RT (a positive interaction) were sufficiently robust to outweigh the pattern observed in RMS error in the perceptual load condition (a negative interaction), so that the total effect on efficiency was that of a positive interaction. They also suggest that when the combined decrement of both tasks is taken into account, there does

appear to be a small but marginally reliable interaction of tracking order with response load. This would indicate the appearance of some degree of response strategies with the increase in tracking order.

Method: Experiment 2

The design of experiment 2 was identical in all respects to that of experiment 1, with the exception that tracking bandwidth was manipulated instead of tracking order. A first order system was always employed and bandwidths of .3 or .5 Hz were used. Four right handed male subjects participated in the experiment.

Results: Experiment 2

Table 2 presents the results of the data for the last six sessions of Experiment 2 in analogous format to the representation of Table 1. Correspondingly, the analyses of the dual task data proceeded in the same manner as the analyses of the data from the first experiment. However, since the single task conditions and the easy level of the dual task conditions were identical between experiments, and the data of Experiment 1 (based upon 8 rather than 4 subjects) were substantially more reliable, only the data from the dual task conditions will be discussed here. The single and easy dual task data in the present experiment showed the same general underadditive trend as in Experiment 1.

Figures 5 & 6 present the data of Experiment 2 in the analogous format to that of Figures 1 & 3 (vis. the separate effects of perceptual, central, and response load on RT and tracking performance). From Figure 5 it is apparent that the perceptual and central load manipulations prolonged RT ($F = 13.5$, $p = .03$; $F = 9.08$, $p = .06$, respectively). RT was not, however,

reliably prolonged by higher bandwidth tracking ($p > .10$ in both cases), nor were the interactions between bandwidth and Sternberg conditions statistically reliable (both F's < 1). In the response load manipulations, none of the three effects were statistically reliable (all P's > .10).

From Figure 6, it is clear that the impact of the tracking bandwidth increase was borne heavily by the tracking track itself (F's = 139, 145, 139, all P's < .01 across the perceptual, central, and response manipulations, respectively). None of the Sternberg variables exerted a reliable increase in tracking error (Perceptual, $F < 1$; Central, $F < 1$; Response, $F = 2.4$, $p > .10$). Finally, there was a weak interaction between the manipulation of central processing load and bandwidth ($F = 6.57$; $p = .08$). Increasing the memory set size improved tracking performance very slightly at the low bandwidth, but deteriorated it at the higher bandwidth. The same sort of interaction appears to be evident in the data of the perceptual and response manipulations, but this interaction failed to reach a level of statistical reliability in either case (both p's > .10).

Finally, it should be noted that the only effect of those examined to influence the error rate on the RT task was the main effect of the response load manipulation. The percentage errors in this case increased from 4.2% (single response) to 7.7% (double response), a reliable ($F = 29$; $p < .01$) effect.

<u>Decrement analysis</u>. Combined decrement scores were calculated, following the same procedure as in Experiment 1, in order to assess the effect of task manipulations on the total cost to both tasks imposed by their concurrence (i.e., the effect of resource competition independent of

resource allocation). This analysis suggests that the decrements are reliably larger at high, as opposed to low bandwidths ($F = 12.7$, $p = .04$). However, decrement size was influenced neither by the Sternberg manipulations, nor by the interaction of Sternberg manipulation and tracking bandwidth (all p's > .10). Therefore, increasing bandwidth appears to produce no selective effect on processing stages.

Discussion

The results of Experiment 1 appear to be somewhat conclusive in localizing the effect of second order tracking in earlier processing stages. Increasing tracking order amplified the effects of both perceptual and central processing load manipulations of a concurrent memory classification task but failed to produce a corresponding interaction with response load when Sternberg RT was examined. When decrements were examined, similar interactions were found with perceptual and central load, while the statistical reliability of the interaction with response load was considerably less. The presence of the interaction with the decrement scores is important in that it indicates that the observed effects were not attributable to the artifact of a resource tradeoff. The similarity of effect on the two processing stages (perceptual and central) is consistent with the model that Wickens (1980) has proposed, arguing that both stages demand access to common resources, separate from those subsuming response processes. The results are also convergent with the conclusions of Wickens, Gill and Donchin (1981), employing evoked potential methodology. Together they suggest the importance of perceiving higher derivatives and complex internal model manipulation involved in second order tracking.

While the results failed to demonstrate any strong evidence for a response-load effect of second order tracking, this conclusion must be drawn with some caution. As noted in the introduction, systems with longer time constants, or operators with lower levels of practice, might clearly generate response loading, while in the current results some evidence for response loading was observed when the decrement scores were examined.

The results of Experiment 2 stand in marked contrast to those of Experiment 1 because Sternberg manipulations were not enhanced in their effects by the more difficult tracking level. A multiple resource interpretation would argue that resources underlying the increased bandwidth are separate from those required when the Sternberg task is prolonged at either of the three stages of processing. In qualifying this conclusion it should be noted that very weak interactions between tracking and Sternberg difficulty are evident with all three Sternberg manipulations, and that the power of this design, with only 4 subjects, is considerably less than that of Experiment 1.

A second interesting contrast between Experiment 1 and 2 concerns the relative effect of the two tracking difficulty manipulations. When bandwidth was increased, a greater increase in tracking error was observed than when order was increased (compare Figure 3 with Figure 6). Furthermore, the increase in bandwidth produced a greater (statistically more reliable) increase in total task decrement than did the increase in order, despite the lesser degree of statistical power in the former case. Thus the absence of interactions with the bandwidth increase cannot be attributed to the inefficiency of this manipulation, nor to the fact that that at high

bandwidths, subjects adopted a filtering strategy in which they simply ignored the higher frequencies of the signal thereby lowering the effective resource demands of the task (Tulga, 1978; McRuer & Jex, 1967).

The theory of resources defined by cerebral hemispheres (Kinsbourne & Hicks, 1978; Friedman & Polson, 1980) provides a possible explanation for the surprising enhancement of tracking performance in the presence of the Sternberg task and its further improvement with the higher levels of perceptual and central processing load observed in Experiment 1. According to their proposed model, resources underlying right hemispheric spatial processing are separate from those subsuming left hemispheric verbal processing. As a task demands more resources from one hemisphere, and more are mobilized to meet the demand, more resources are simultaneously mobilized from the other. Therefore, if two tasks are time-shared that draw upon separate hemispheres, increasing the difficulty of the first can improve performance on the second as resources are mobilized to cope with this second task. In the present case, we assume that tracking, because of its spatial elements, is primarily localized in the right-hemisphere. The incremental demand imposed by requiring the verbal Sternberg task imposes a load on resources in the left hemisphere. The consequent mobilization of more right hemispheric (spatial) resources facilitates the increase in tracking performance. The further increase in resource demand upon the left hemisphere imposed by the mask and memory set manipulation leads to further mobilization of spatial resources. A residual decrease in tracking error consequently results.

Naturally, other explanations are possible as well. It is conceivable,

for example, that there may have existed motivational differences between single and dual task conditions that lead to the tracking performance increment, despite instructions and a payoff system that stressed maximum performance in all conditions. While Kahneman (1973) does argue for the plausibility of an "expanded capacity" in dual task conditions, he argues also that the expansion of capacity is never sufficient to compensate for the increase in total task load. Therefore, this conception cannot account for the actual increase in tracking performance.

One final aspect of the results concerns the relative degree of additivity (or slight underadditivity) found between the Sternberg variables and the addition of the tracking task. This is a trend that has been observed in other dual task applications of the Sternberg task (Micalizzi & Wickens, 1980): there is a large cost in reaction time attributable to the presence of the primary task, but this cost does not appear to be borne by a particular processing stage. In fact, the effects of some stage manipulations appear to be attenuated, or "hidden" by this overall prolongation. Logan (1978) has attributed this main effect to an overall preparatory set that must occur in the presence of the primary task. Once this set is adopted, which prolongs reaction time in general, all stages are assumed to proceed at their normal single task rate.

Alternatively, a discrete attention switching strategy may occur. According to this interpretation, attention is normally focussed on the primary, continuous tracking task. When the unpredictable Sternberg stimulus occurs, attention, or perhaps "conscious processing" is switched discretely to the stimulus. Once processing begins, it proceeds at its

normal rate; therefore the additivity with Sternberg manipulations of single to dual task RT effects is observed. In fact, processing might occur slightly more rapidly as a consequence of the cross-hemispheric resource mobilization described above. Therefore the underadditivity is observed. This explanation must assume that some resources are continuously available to the tracking task. When the task is then made more difficult in ways that consume resources also demanded by Sternberg processing (e.g., by the increase in perceptual and central processing requirements of anticipation in second order tracking), this depletion of resources to the RT task produces the magnification of the effects of central perceptual processing load. One piece of evidence in support of the attention-switching hypothesis for underadditivity of dual task loading, is the frequent occurrence of this effect in paradigms in which an auditory Sternberg task has been employed with a visual primary task (e.g., Spicuzza, Pincus, & O'Donnell, 1974, see Table 1 of Micalizzi & Wickens, 1980). If there is, in fact, greater prolongation of attention-switching between than within modalities (Laberge, Van Gelder & Yellott, 1969), then this delay might conceivably represent the source of the prolongation.

In summary, the results serve simulaneously to validate the Sternberg task as a selective index of task load, to support the conceptual division of resources along a stage-of-processing dimension, and to localize the effect of higher order control at the earlier stages. While the greater load of higher order control is well established, the suggestion that its interference effects with concurrent perceptual and cognitive tasks might be more damaging than with concurrent motor tasks represents an important

implication of the present research.

Footnote

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Table 1

Sternberg Task RT (msec)

	Easy	Mask (perceptual load)	N = 4 (central load)	Double Response (response load)
Single Task	538	562	588	562
1st Order	613	626	642	619
2nd Order	624	667	684	641

Tracking RMS Error

	Easy	Perceptual	Central	Response	Single Task Control
1st Order	.114	.108	.107	.111	.116
2nd Order	.176	.161	.161	.172	.182

Table 2

Bandwidth Manipulation

Sternberg Task RT (msec)

	Easy	Mask (Perceptual Load)	N=4 (Central Load)	Double Response (Response Load)
Single Task	509	536	555	533
Low BW	565	574	584	583
High BW	569	583	590	581

Tracking RMS Error

	Easy	Perceptual	Central	Response	Single Task Control
Low BW	.092	.088	.091	.094	.093
High BW	.162	.164	.166	.166	.162

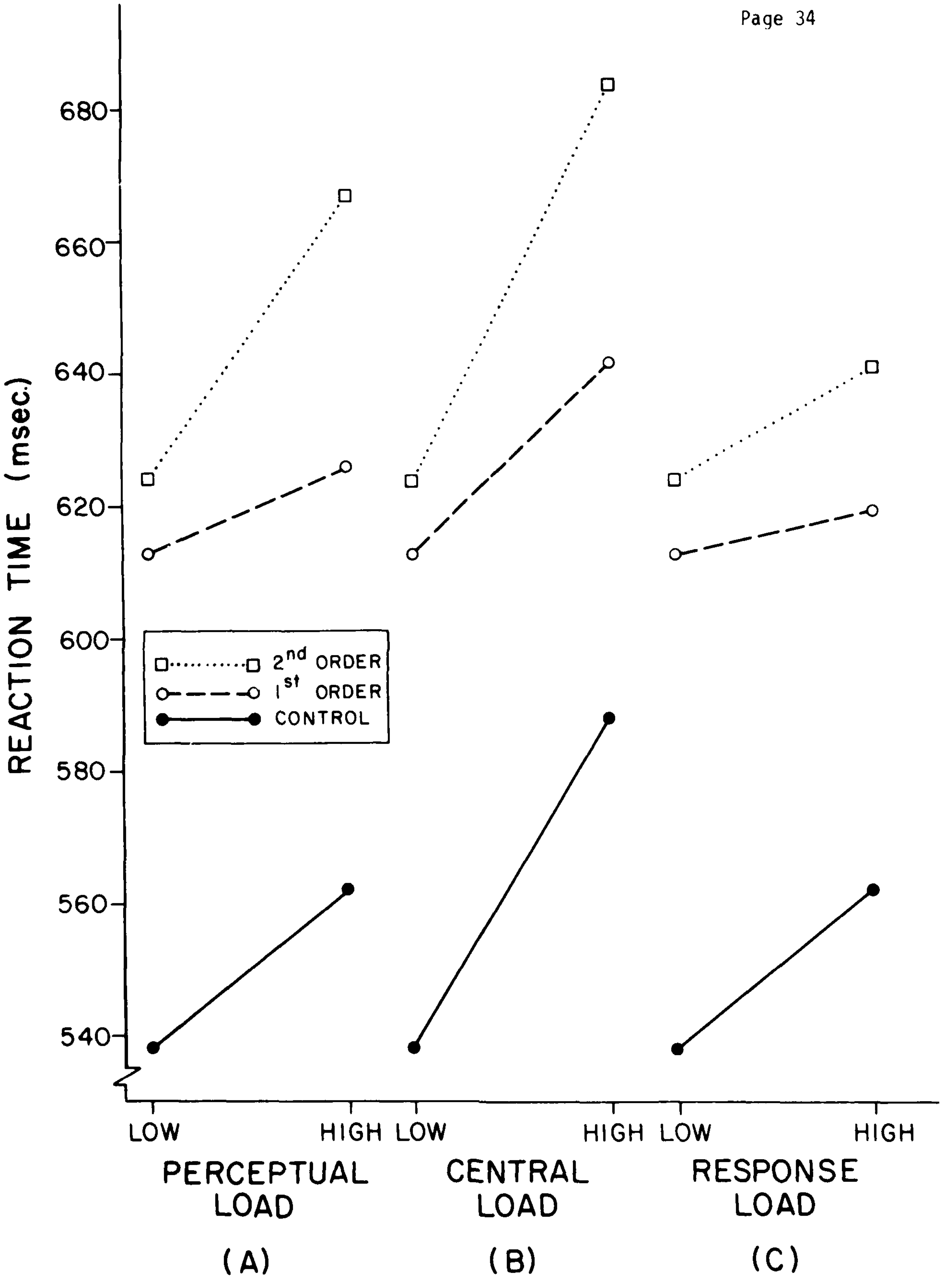

FIGURE 1: Effect of tracking order and Sternberg variables on Sternberg correct RT.

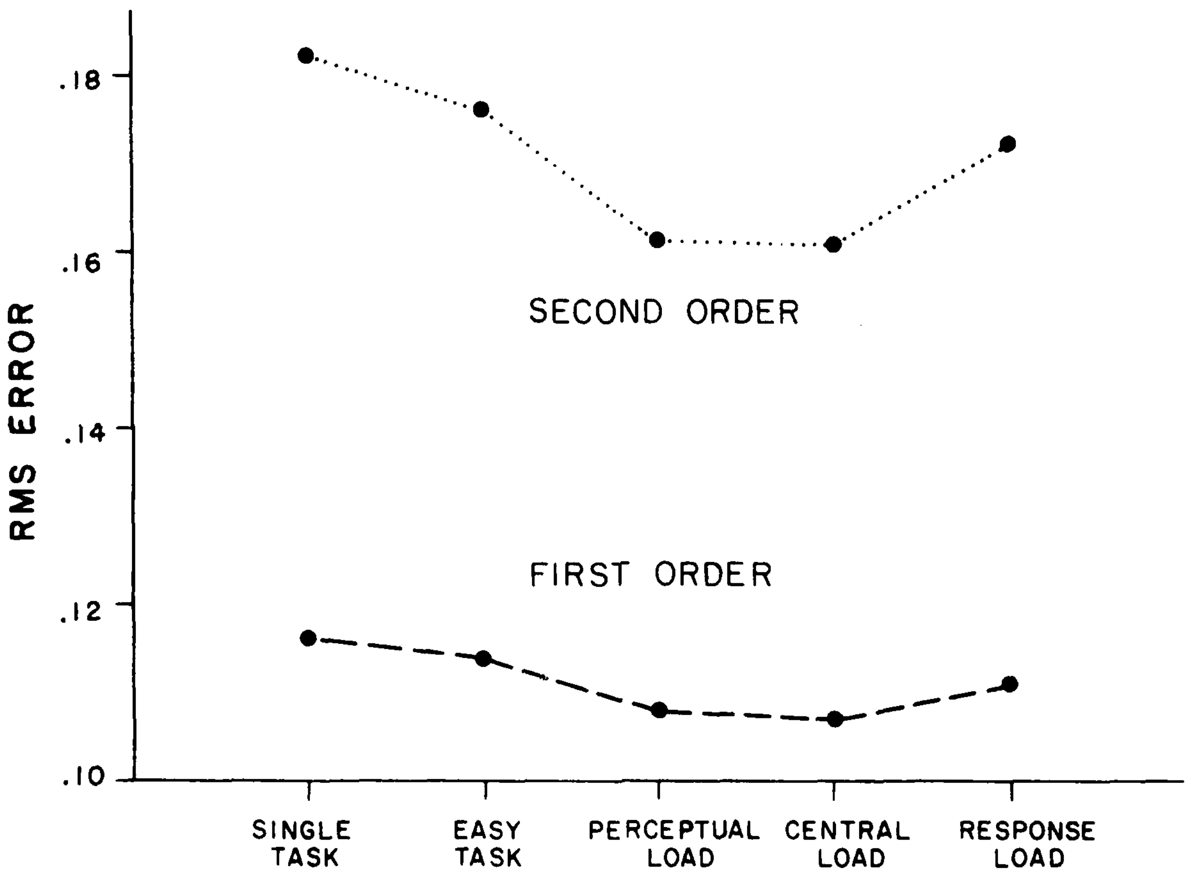

FIGURE 2: Effect of tracking order and Sternberg variables on tracking RMS error.

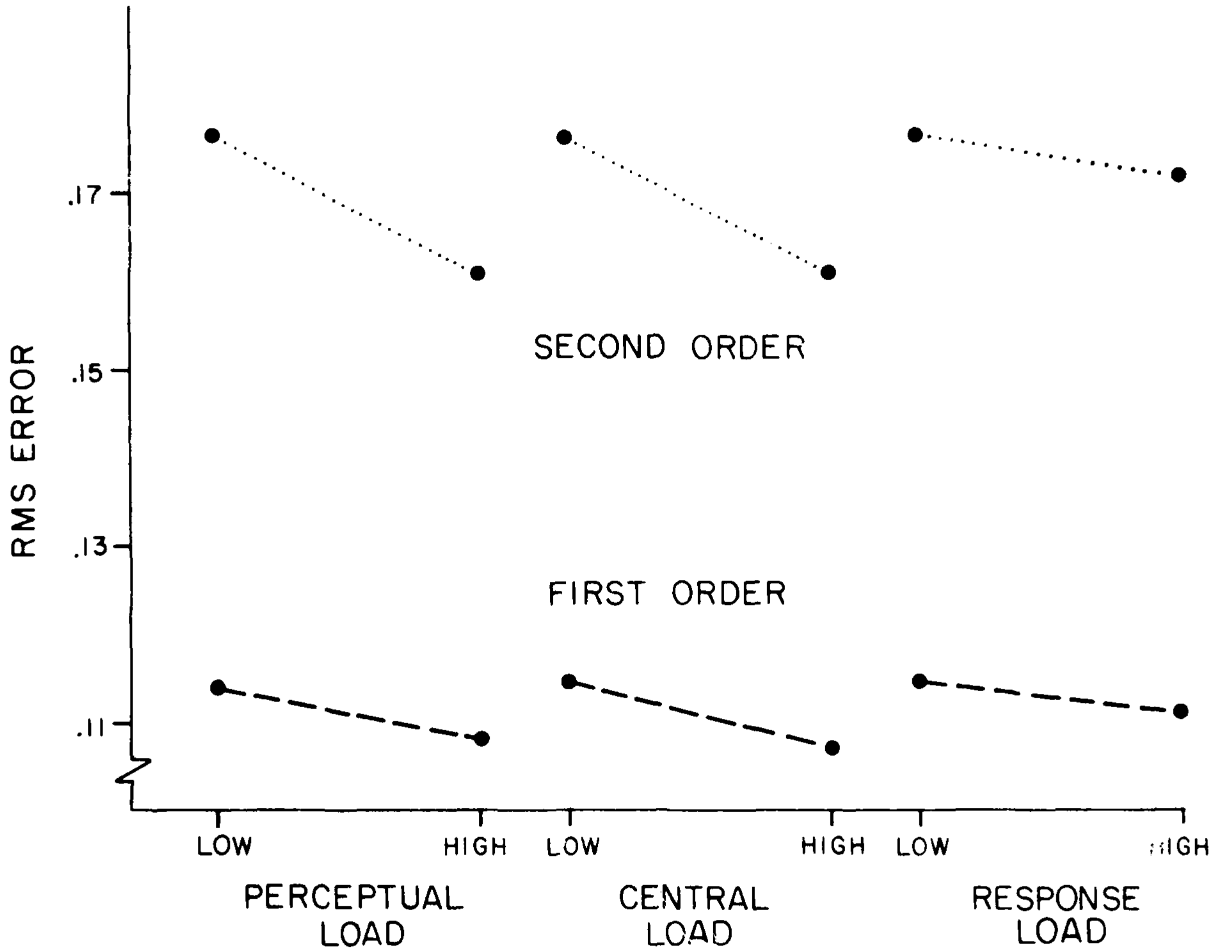

FIGURE 3: Effect of tracking order and Sternberg variables on tracking RMS error.

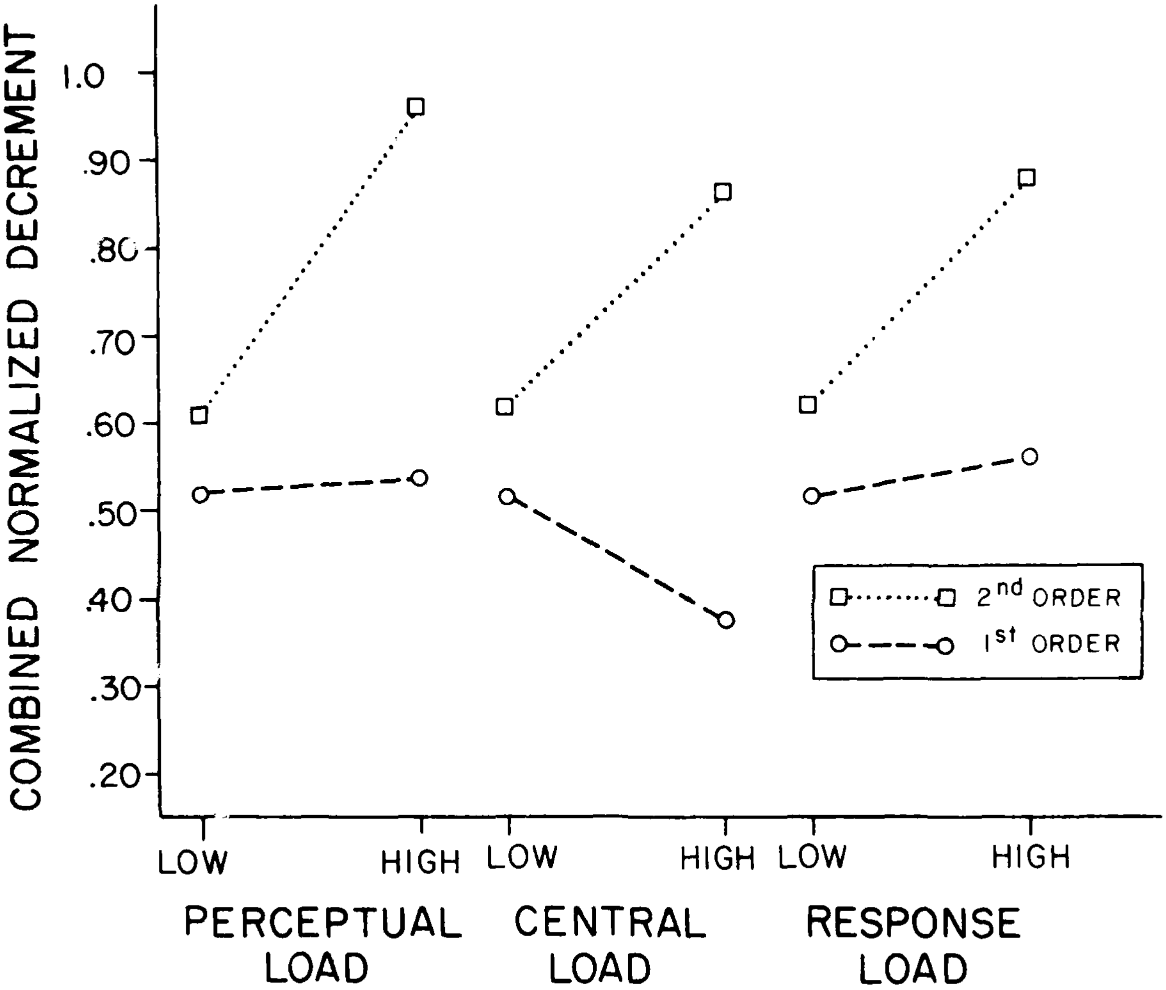

FIGURE 4: Effect of tracking order and Sternberg variables on the combined, normalized decrement of both tasks.

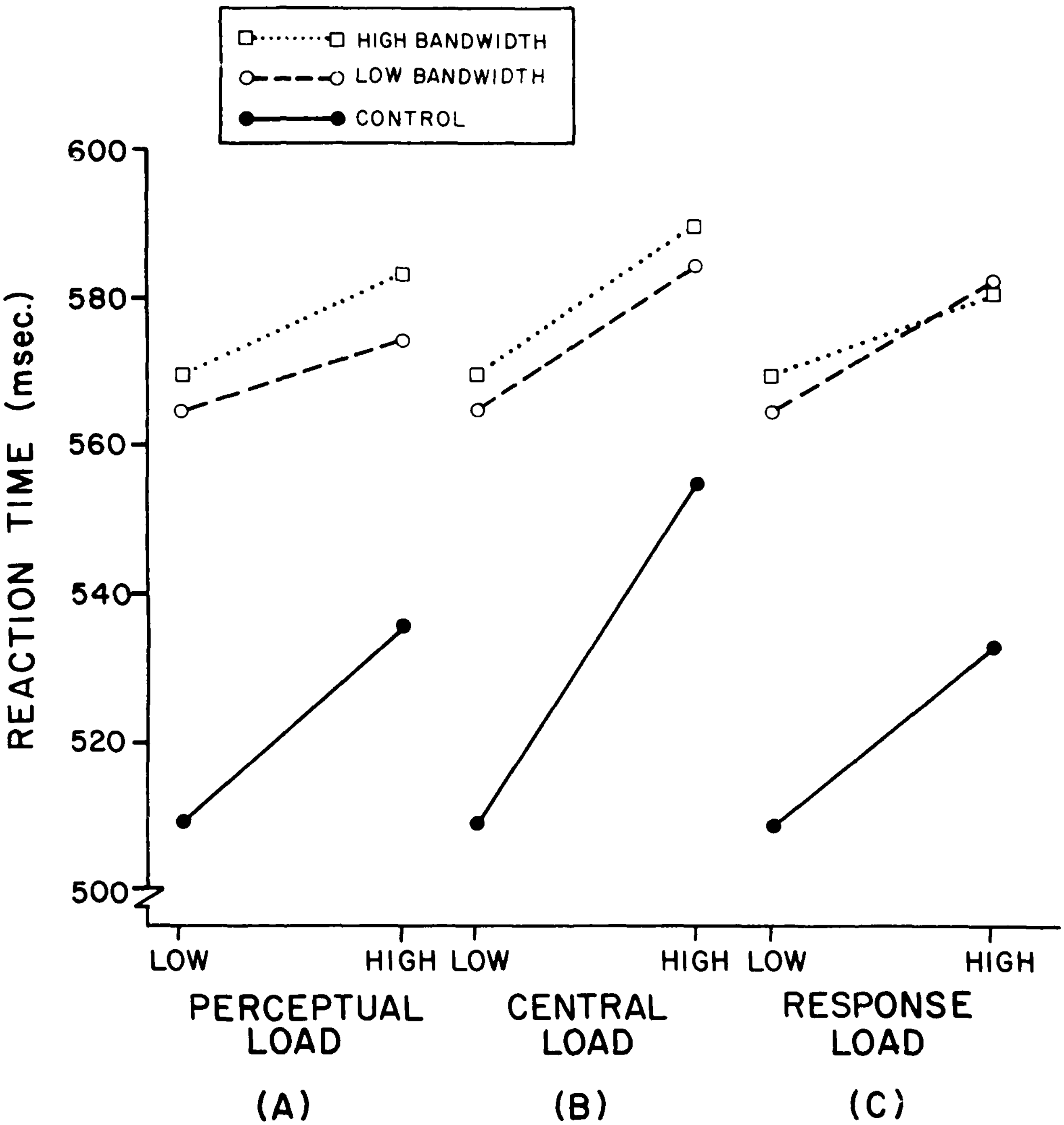

FIGURE 5: Effect of tracking bandwidth and Sternberg variables on RT.

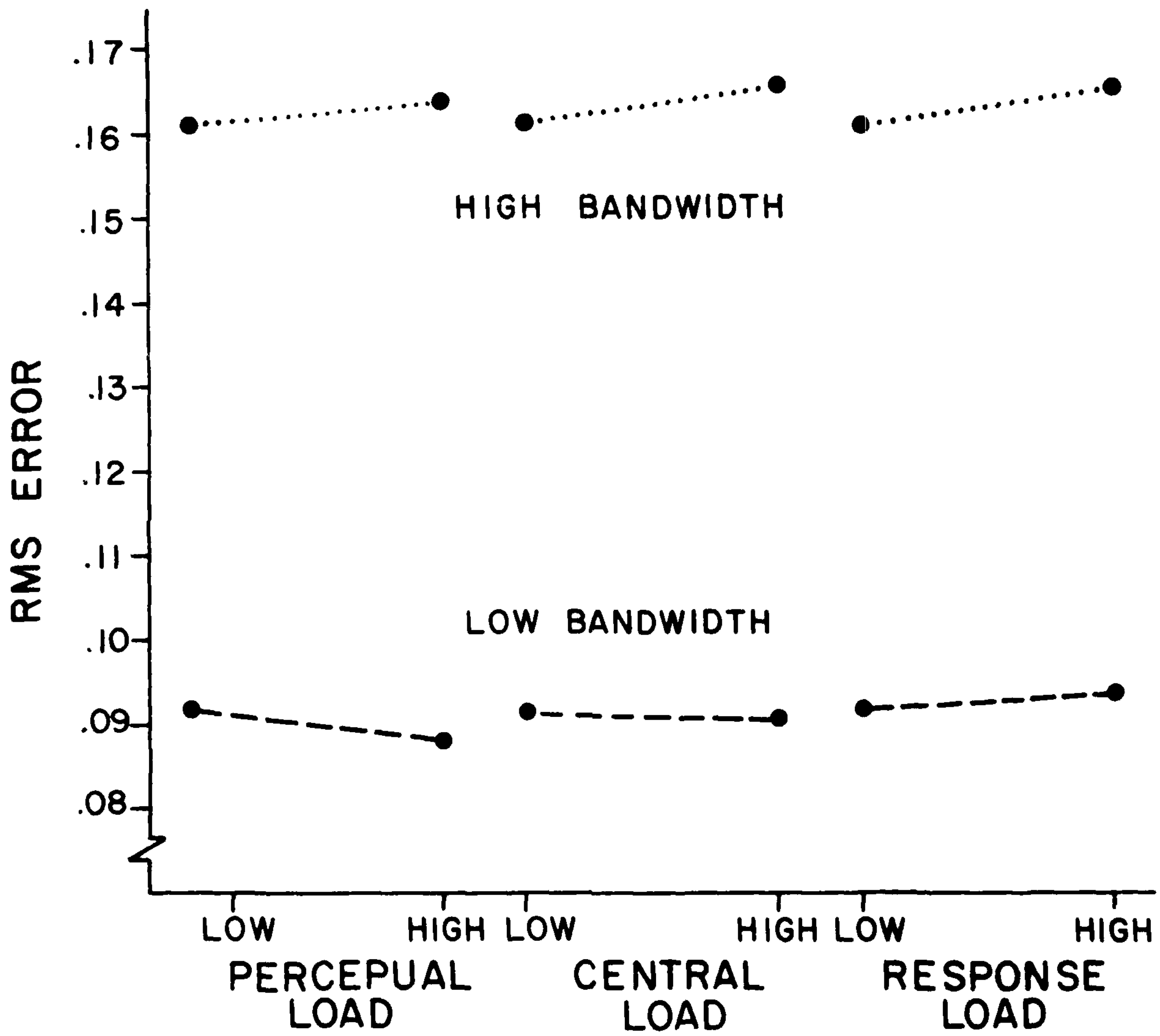

FIGURE 6: Effect of tracking bandwidth and Sternberg variables on tracking RMS error.

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